Energy & Technology Review

■ *The Clementine Satellite Maps the Moon*

■ *Uncertainty and the Federal Role in Science and Technology*

University of California

Lawrence Livermore National Laboratory

About the Cover

The Clementine satellite was launched from Vandenberg Air Force Base on January 25, 1994. Sponsored by the Department of Defense's Ballistic Missile Defense Organization, the spacecraft carried six lightweight cameras and a laser ranger developed by LLNL. These cameras, two of which are shown in the foreground, were used to map the entire surface of the Moon at spatial resolutions never before attained. Images of Earth were also returned from selected cameras. One such image (shown in background), taken at a distance of 174,000 km, shows a view of Earth against the blackness of space. See the article on p. 1 for more spectacular views of the Moon and Earth and a description of each of the LLNL-developed sensors.

About the Journal

The Lawrence Livermore National Laboratory, operated by the University of California for the United States Department of Energy, was established in 1952 to do research on nuclear weapons and magnetic fusion energy. Since then, in response to new national needs, we have added other major programs, including technology transfer, laser science (fusion, isotope separation, materials processing), biology and biotechnology, environmental research and remediation, arms control and nonproliferation, advanced defense technology, and applied energy technology. These programs, in turn, require research in basic scientific disciplines, including chemistry and materials science, computing science and technology, engineering, and physics. The Laboratory also carries out a variety of projects for other federal agencies. *Energy and Technology Review* is published monthly to report on unclassified work in all our programs. Please address any correspondence concerning *Energy and Technology Review* (including name and address changes) to Mail Stop L-3, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94551, or telephone (510) 422-4859.

Prepared for **DOE** under contract
No. W-7405-Eng-48

■ June 1994

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

UCRL-52000-94-6
Distribution Category UC-700
June 1994

Energy & Technology Review

The Clementine Satellite

The Clementine satellite tested 23 advanced technologies during its mission for the Ballistic Missile Defense Organization. In fulfilling its scientific goals, Clementine provided a wealth of information relevant to the mineralogy of the lunar surface. Using six on-board cameras designed and built at the Laboratory, Clementine mapped the entire surface of the Moon at resolutions never before attained. Clementine also provided range data that will be used to construct a relief map of the lunar surface.

THE first U.S. satellite to the Moon in more than two decades was launched from Vandenberg Air Force Base (Santa Barbara County), California, on January 25, 1994. The satellite (Figure 1) was named Clementine because it carried only enough fuel to complete its mission before it was "lost and gone forever," as in the old ballad "My Darling Clementine."

The satellite orbited the Moon for more than two months beginning February 19, taking and transmitting high-resolution pictures and range data until it built up a detailed map of the entire lunar surface. Clementine completed its lunar orbit on May 3, 1994, sending back more than 1.5 million images of the Moon.

The Planned Mission

Clementine's primary mission was to demonstrate in the harsh environment of space advanced, lightweight technologies developed by the Department of Defense for detecting and tracking ballistic missiles. Its sensor suite consisted of six state-of-the-art cameras, and the basic system included many other new lightweight technologies, such as inertial measurement units, reaction wheels, a battery, a computer, and a solid-state recorder. Clementine used the Moon and the spacecraft's own solid-rocket motor (after it separated from the satellite) as targets to demonstrate how the lightweight components and sensors would perform during flight.

Clementine's secondary mission—and the main focus of this article—was to return valuable information of interest to the scientific community. Clementine represents a new class of small, low-cost spacecraft suitable for long-duration missions into deep space. In this respect, it can open the door to new scientific missions, such as planetary exploration, that are much more cost-effective and have a quicker return of data. Moreover, Clementine completely mapped the lunar surface in 14 discrete spectral bands ranging from the near ultraviolet (0.415 μm), through the visible spectrum, to the far infrared (9.5 μm). Although Clementine involved the participation of many organizations and had several different objectives (see the box on p. 2 for more details), the primary objective was to test the optical sensors developed by LLNL.

The last phase of the scheduled mission was to be a flyby of the near-Earth asteroid Geographos, which is about 5 km long and crosses Earth's orbit about every 18 months. Even though near-Earth asteroids tend to be much larger than missiles, Geographos would have provided a meaningful target as Clementine attempted a near-miss intercept using the new sensor technologies. This flyby was also expected to provide the first close-up view of an Apollo asteroid and spectral information relevant to its surface geology. The combined lunar and asteroid data would add to our knowledge of the solar system and its evolution.

After successfully mapping the Moon, Clementine left lunar orbit and began its journey to Geographos on May 5. On May 7, however, one of the on-board processors failed and turned on the attitude-control thrusters, which sent the spacecraft into a spin (81 revolutions/minute). That failure drained the attitude-control system of its fuel (although there was still fuel for the main thruster), effectively canceling the Geographos portion of the mission. At this angular velocity, Clementine could still have flown to Geographos, but it would not have sent back useful images, and contact with it probably would have been lost. As a result, Clementine spent its final days orbiting Earth, continuing to collect lifetime data on the new on-board technologies. Although the asteroid portion of the mission was not completed, the principal instruments and sensors functioned extremely well, and Clementine is viewed as a landmark project in terms of cost effectiveness and its demonstration of next-generation components and technologies.

Some Facts About Clementine

Clementine is a Department of Defense program to demonstrate a new generation of technology for both military and civilian space applications. Clementine is also known as the Deep Space Program Science Experiment. It is the first in a series of technology demonstrations sponsored by the Ballistic Missile Defense Organization—formerly called the Strategic Defense Initiative Organization.

Clementine is an example of one of the "smaller, cheaper, faster" satellites. Despite a degree of technical risk, this approach showed that data could be returned promptly from the lunar surface without the large monetary and time investment required of a more traditional approach.

The total cost of the project, including mission control and the launch vehicle, was $75 million. In this respect, Clementine is a landmark satellite because it demonstrates that small, highly capable satellites can be built and launched for under $100 million using advanced, miniaturized technology and a streamlined management approach.

The total time from initial concept to launch of the satellite was about 22 months. This time included hardware design, procurement and fabrication, assembly, integration, and test. This short development time was made possible because a dedicated team was responsible for all phases of the effort and followed the satellite's development from concept to launch and operation.

The Naval Research Laboratory designed, fabricated, integrated, and operated the spacecraft. NASA's Goddard Space Flight Center and the Jet Propulsion Laboratory provided design support. The NASA Deep Space Network helped the Naval Research Laboratory track and communicate with Clementine. Lawrence Livermore National Laboratory designed, developed, and calibrated the suite of on-board Clementine imaging and ranging sensors.

The launch vehicle was a Martin Marietta Titan IIG ballistic missile. It carried two experiments into space: the Clementine satellite for lunar mapping, and a solid-rocket motor containing several radiation detectors to take measurements in Earth's radiation belts. The rocket motor is expected to orbit Earth for more than a year, passing through the radiation belts twice per orbit. In addition to using celestial bodies as imaging targets, Clementine also tracked and imaged the rocket motor as a test of the missile-imaging capability of the sensor suite.

In launch configuration, Clementine had a total mass of 1690 kg, including the solid-rocket motor. The dry mass of the satellite was 228 kg, and it carried 200 kg of fuel.

Launch and the Orbit Path

The launch vehicle for Clementine was a refurbished Martin Marietta Titan IIG ballistic missile, which carried one other experiment in addition to the Clementine satellite. On December 29, 1993, Clementine was delivered to Vandenberg Air Force Base for integration to the Titan IIG launch vehicle and was launched on January 25, 1994.

Clementine followed a complicated path on its way to the Moon. To minimize the amount of required on-board fuel (and, therefore, the total mass of the spacecraft), Clementine completed two and one-half looping orbits about Earth's poles after leaving low-Earth orbit and before going into lunar orbit. Technically known as "phasing" loops, the path consisted of elliptic orbits with a large eccentricity. These phasing loops provided a more precise measurement of the satellite's position and minimized the number of velocity adjustments needed prior to lunar orbit. Figure 2 shows the path of the spacecraft prior to entering lunar orbit.

An on-board solid-rocket motor boosted the spacecraft into its initial phasing loop—with a perigee of 277 km and an apogee of ~170,000 km. This initial phasing loop was also used to insert the solid-rocket motor into its planned orbit. Another firing of the

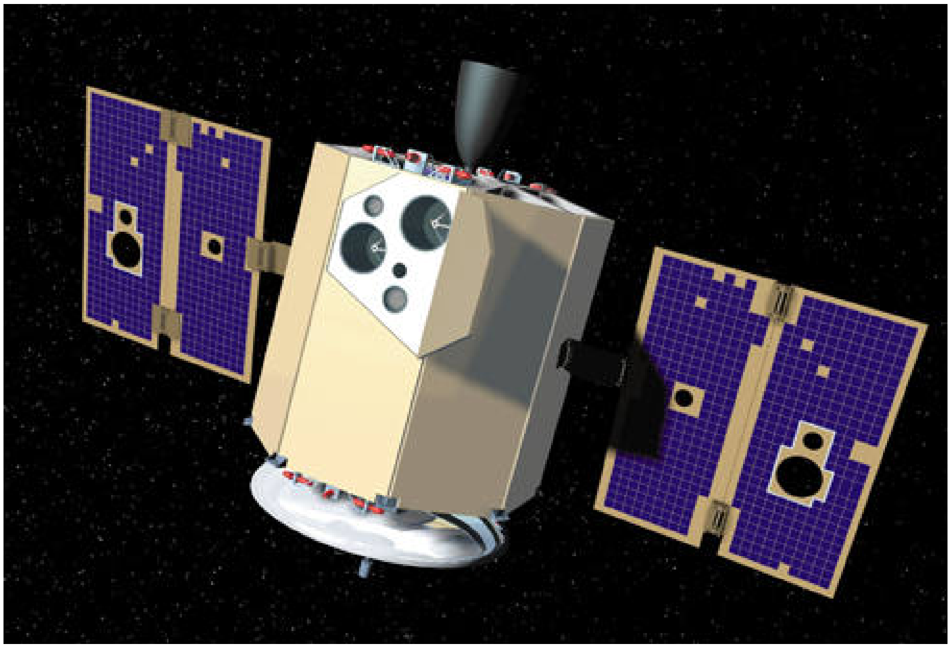


Figure 1. The Clementine satellite was designed to demonstrate performance of lightweight imaging sensors and component technologies developed for the Ballistic Missile Defense Organization. This spacecraft measured 1.88 m in diameter and was 1.14 m long.

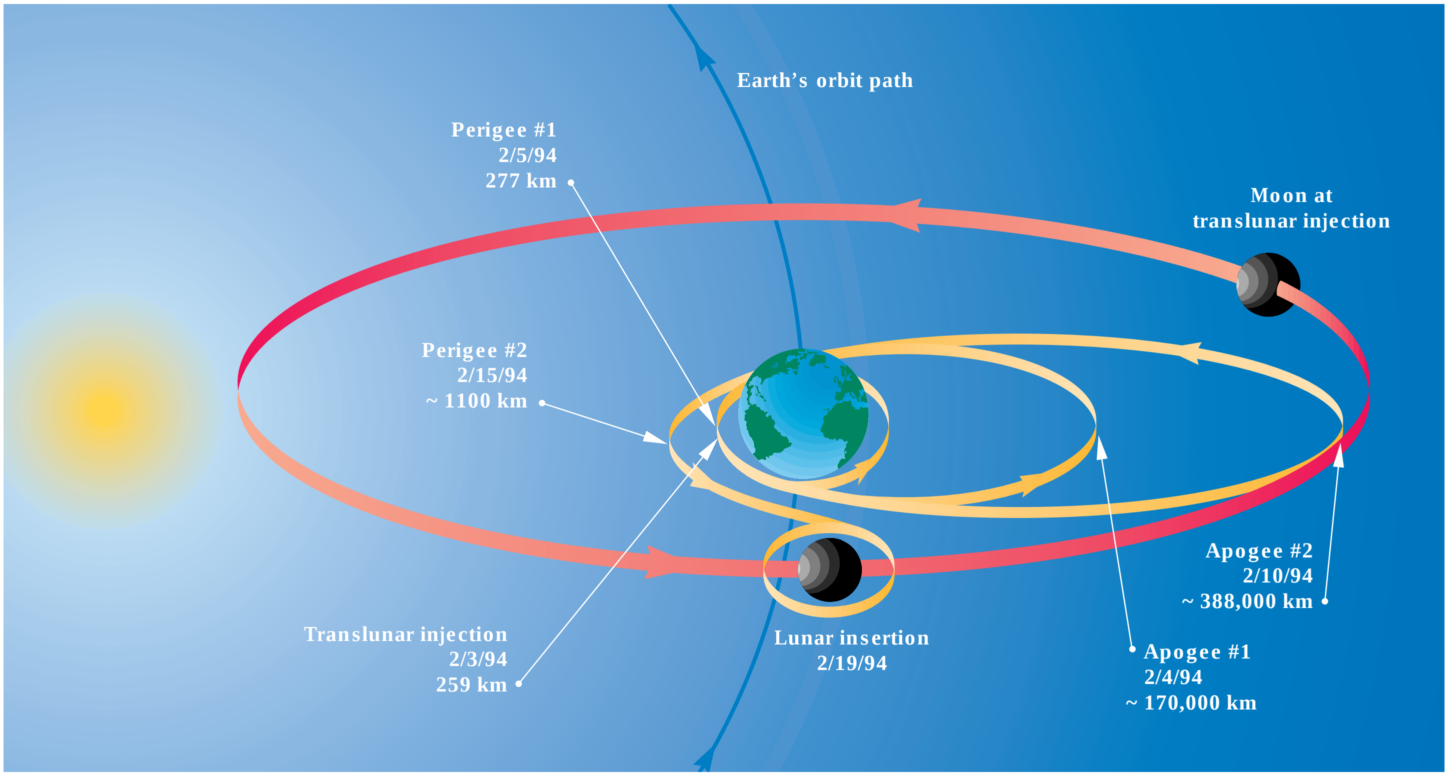


Figure 2. Path of Clementine on its way to the Moon. The spacecraft completed two and one-half phasing loops about Earth's poles before entering lunar orbit.

main thruster boosted the spacecraft into its final phasing loop with an apogee of ~388,000 km.

On February 19, Clementine began its orbit of the Moon. Initially, it was placed in a polar orbit with a period of 5 hours (Figure 3a). During its 70 days of orbit, Clementine's imaging sensors were, for the most part, pointed directly down to the lunar surface as it passed over the sunlit side. To maintain a near constant solar illumination of the surface during imaging, the orbit was adjusted half way through the mapping phase (Figure 3b). To obtain images of surface features under different lighting conditions, the cameras also took images at selected oblique angles. In addition, the cameras took images of the dark space background in order to verify that the camera's dark levels and performance had not changed during the mission.

The Cameras and Sensors

The Laboratory, with the support of its industrial contractors, was responsible for the design, development, and flight qualification of seven lightweight spacecraft sensor components for the Clementine mission. Table 1 lists the mass of each sensor, which altogether totaled only 0.32% of the dry mass of the satellite. Table 2 lists the field of view and the instantaneous field of view (i.e., angular measure of a pixel)

Table 1. Mass of LLNL-developed sensors for the Clementine mission.

Sensor	Mass, kg
Star Tracker 1	0.280
Star Tracker 2	0.286
Ultraviolet/visible camera	0.426
High-resolution camera	1.120
Laser transmitter	0.635
Laser transmitter power supply	0.615
Near-infrared camera	1.880
Long-wave infrared camera	2.075
Total mass of sensors	**7.32**

Table 2. Performance of LLNL-developed sensors for the Clementine mission.

Sensor	Field of view, deg × deg	Instantaneous field of view, μrad	Image size, km × km*	Resolution, m*,†
Star Tracker	28.9 × 43.4	1.31 × 1.31	–	524
Ultraviolet/visible camera	4.2 × 5.6	255	29.30 × 39.10	108
High-resolution camera	0.3 × 0.4	18	2.09 × 2.97	8
Near-infrared camera	5.6 × 5.6	396	39.12 × 39.12	168
Long-wave infrared camera	1.0 × 1.0	143	6.98 × 6.98	61

*Image size and resolution are based on periselene (closest approach) of 400 km.
†Theoretical limit.

(a) Typical lunar mapping orbit—first month

(b) Typical lunar mapping orbit—second month

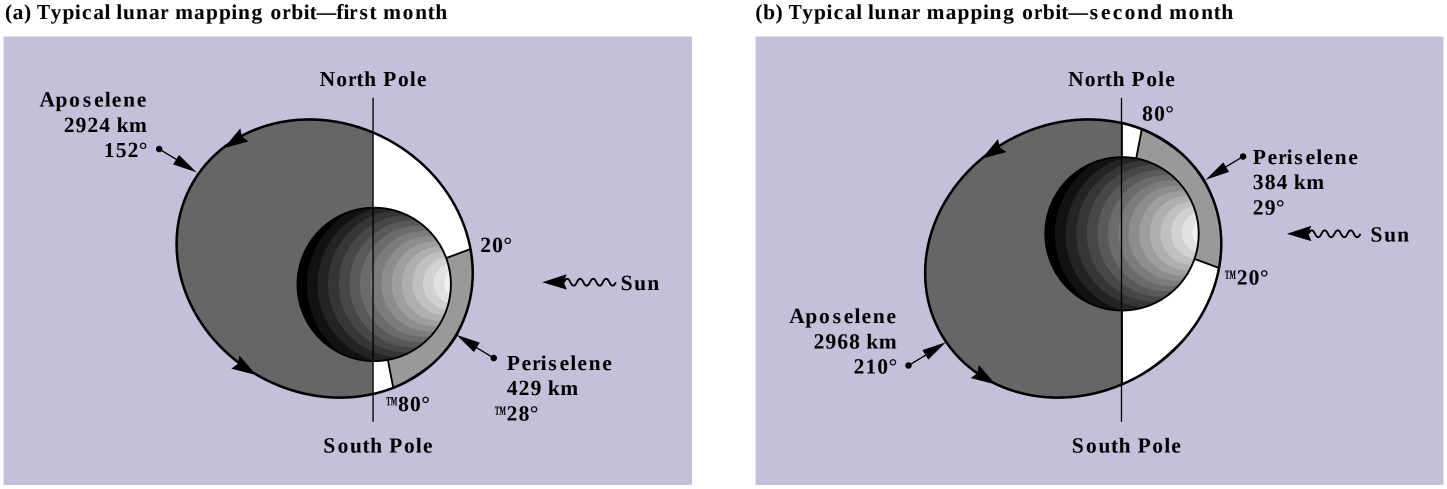


Figure 3. Typical lunar orbits during the first (a) and second (b) months of mapping. The orbit was adjusted to maintain a near constant solar illumination of the surface during imaging. The Clementine satellite orbited the Moon from the South Pole to the North Pole, obtaining optimal range measurements between –80 deg and +80 deg latitude (light shading) and images between –90 deg and +90 deg latitude (white). Also shown are the aposelene (farthest approach) and periselene (closest approach) of the satellite to the Moon.

of each camera on board the spacecraft. Also listed are the areal coverage and the theoretical resolution for each sensor at a close approach to the Moon.

Altogether, Clementine's sensor package imaged the Moon in 14 selectable, narrow-wavelength bands ranging from 0.415 μm to 9.5 μm. The cameras were equipped with a set of special color filters selected to provide the maximum amount of information about the surface mineralogy of the Moon and Geographos. The images and other data returned from lunar mapping cover 100% of the Moon's surface at spatial resolutions that cannot be obtained from observatories on Earth.

Common rock-forming minerals on the Moon and in meteorites can be identified by color in the visible and infrared portion of the spectrum. Major silicate minerals can be recognized by their absorption of particular colors in the near-infrared from reflected sunlight (see Figure 4). Thus, rocks composed of various amounts of these minerals can be distinguished and mapped by means of the multispectral images taken with Clementine's cameras.

In addition, Clementine's light detection and ranging (LIDAR) system was selected to make detailed measurements of the relative heights of features on the Moon. The information it provided will be used to develop a three-dimensional map of a selected portion of the lunar surface.

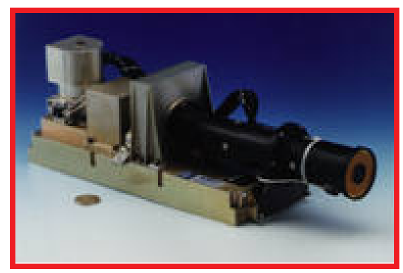
Wide-Field-of-View Star Trackers

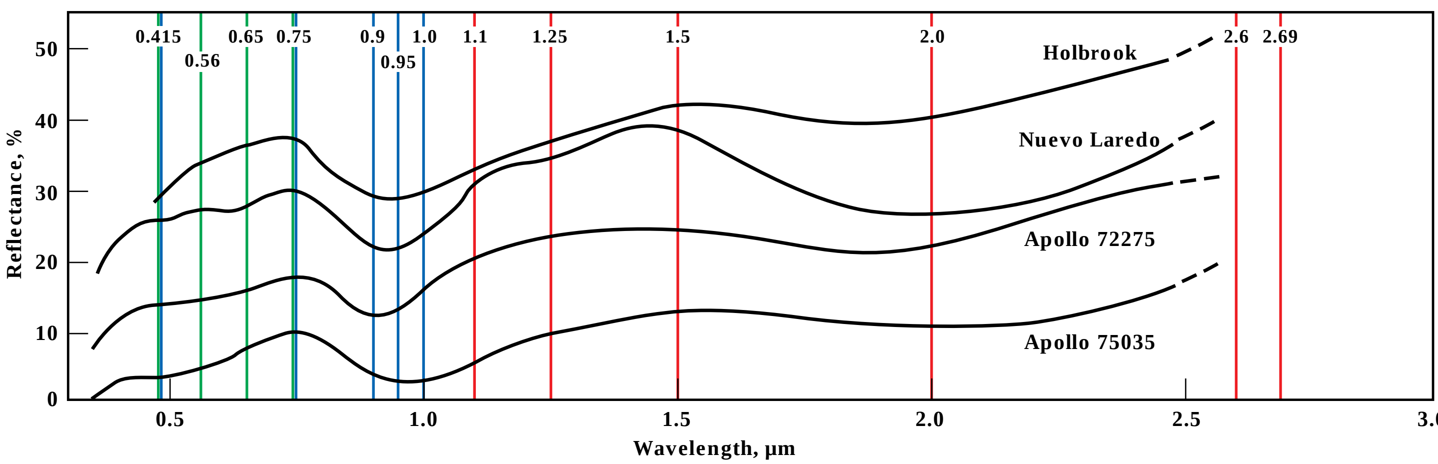
Two units on Clementine, called Star Tracker Stellar Compasses, provided inertial reference for the Clementine spacecraft by comparing images of star fields with an on-board star map. The two Star Trackers were designed, tested, and built by the Laboratory and its contractors. The Star Tracker is a digital camera and

High-resolution camera

Ultraviolet/visible camera

Near-infrared camera





Electromagnetic spectrum from 0.3 to 3 µm

Ultraviolet Visible Infrared

Figure 4. The graph shows the diffuse reflectance of samples of extraterrestrial materials as a function of wavelength. These samples, returned to Earth from various space missions, provided us with the wavelengths of interest in designing the cameras and sensors for Clementine. The vertical lines in the graph indicate the center wavelengths of the filters for the cameras, three of which are shown here. The filters used for each camera can be identified by matching the color of the filter line to that of the box surrounding the camera. Also shown is the relevant portion of the electromagnetic spectrum.

weighs only 0.29 kg (Figure 5a). The camera has a wide (29 deg by 43 deg) field of view and can detect stars down to a visual magnitude of 4.5. The camera, in combination with a highly sophisticated star-matching algorithm and an on-board star catalog, provides spacecraft attitude with respect to the celestial sphere.

To use stars for navigating, the star-matching algorithm scans each image obtained, such as the one shown in Figure 5b, and generates a series of triangles using the twelve brightest objects in the image. These triangles are compared to an on-board database of triangles from 500 star positions listed in a whole-sky star catalog. If a candidate star turns out to be some other object, such as a planet that is not in the correct position to be a star, the Star Tracker algorithm ignores the object.

The Star Tracker was also used to image both the Moon and Earth. Figure 6 shows the Star Tracker's view of the airglow of Earth and the light from urban areas. Figure 7 shows a composite of the Moon made from six separate Star Tracker images.

Ultraviolet/Visible Camera

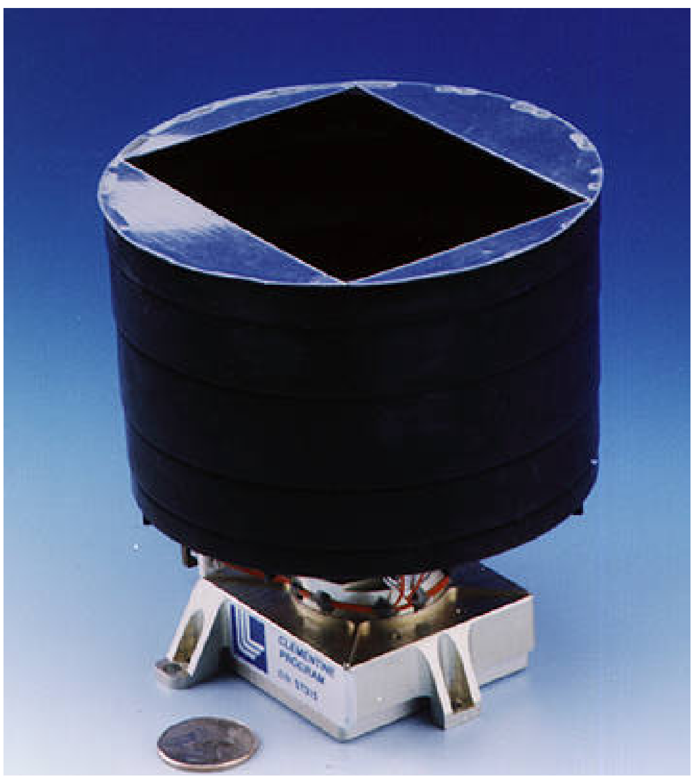
To provide reliable, solid-state, cost-effective imaging in the near-ultraviolet, visible, and near-infrared regions of the spectrum (from 0.3 to 1.0 μm), LLNL designed and built a medium-resolution, 0.426-kg camera that uses silicon charge-coupled device (CCD) technology. For Clementine, this camera was combined with a six-position spectral filter wheel for remote sensing applications and, specifically, for mineral typing studies of the Moon.

Figures 8a through 8e show the African continent imaged by the ultraviolet/visible camera at five different wavelengths on a clear day from a distance of 384,000 km. Figure 8f is a composite view. Figure 9 shows the crater Tycho on the Moon, which is about 80 km in diameter; Figure 10 is an image mosaic of the lunar South Pole showing a dark depression at the center.

Near-Infrared Camera

This 1.9-kg camera, produced by LLNL and Amber Engineering, uses a cryogenically cooled indium–antimonide array to provide solid-state imaging from the near-infrared (0.9-μm) region to the short-wave-infrared (3.1-μm) region at medium resolution. The Laboratory combined the camera with a modular, six-position spectral filter wheel to obtain data in discrete spectral bands.

(a)



(b)

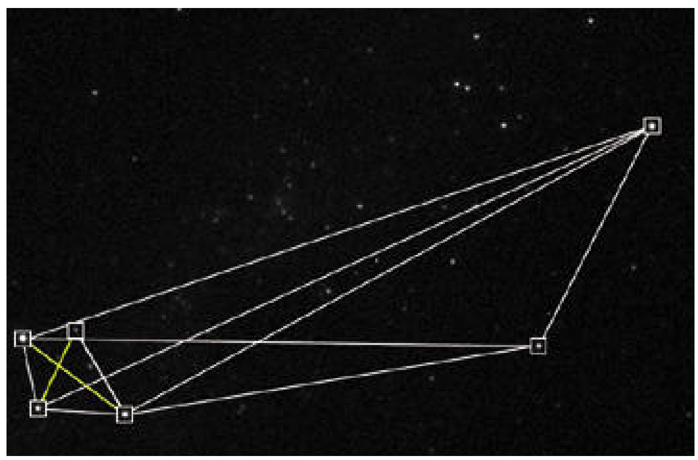


Figure 5. (a) Two Star Tracker Stellar Compasses were used to provide inertial reference for the Clementine satellite. Each Star Tracker weighed only 0.29 kg. (b) This image was taken by the Star Tracker on February 15, 1994, from the Clementine spacecraft during its second loop around Earth prior to lunar orbit. Triangles illustrate how a star match is achieved by comparing the position of detected objects with an on-board database of triangles prebuilt from star positions listed in a whole-sky star catalog. In this case, a match with the Southern Cross constellation, shown in yellow, was achieved.

During the Clementine mission, the spectral bands covered by the near-infrared camera allowed scientists to obtain mineral typing data for 100% mapping of the Moon. Figure 11 shows a view of several lunar craters captured by the near-infrared camera; Figure 12 shows a view of the 35-km-diameter Rydberg crater.

High-Resolution Camera

This 1.1-kg camera operates at visible wavelengths (0.415 to 0.75 μm) with silicon CCD technology combined with a compact, lightweight image intensifier. A six-position, spectral filter wheel provided imagery in discrete spectral bands.

As an example of the camera's capability, Figure 13 shows an image of Earth taken by the high-resolution camera from lunar orbit at 1250 km above the surface of the Moon and at a distance of 384,000 km from Earth. During the lunar-mapping portion of Clementine, the camera produced high-resolution images for mineral typing of the lunar surface.

LIDAR System

The optics of the high-resolution camera also served another purpose on the Clementine mission, namely ranging. (Range measurements in the context of orbiting the Moon are measurements of the distance from the spacecraft to the lunar surface.) The laser-ranging altimeter shared the optics of the high-resolution camera and was used to obtain altitude measurements during mapping orbits around the Moon. The LIDAR was used to determine the relative heights of features on the Moon's surface.

A compact, lightweight, diode-pumped, neodymium, infrared (1.06 μm) laser manufactured by McDonnell Douglas Corporation provided the high-energy pulses (180 MJ) needed for ranging at lunar distances. In essence, the laser transmitter pinged the Moon's surface from an altitude as far as 640 km.

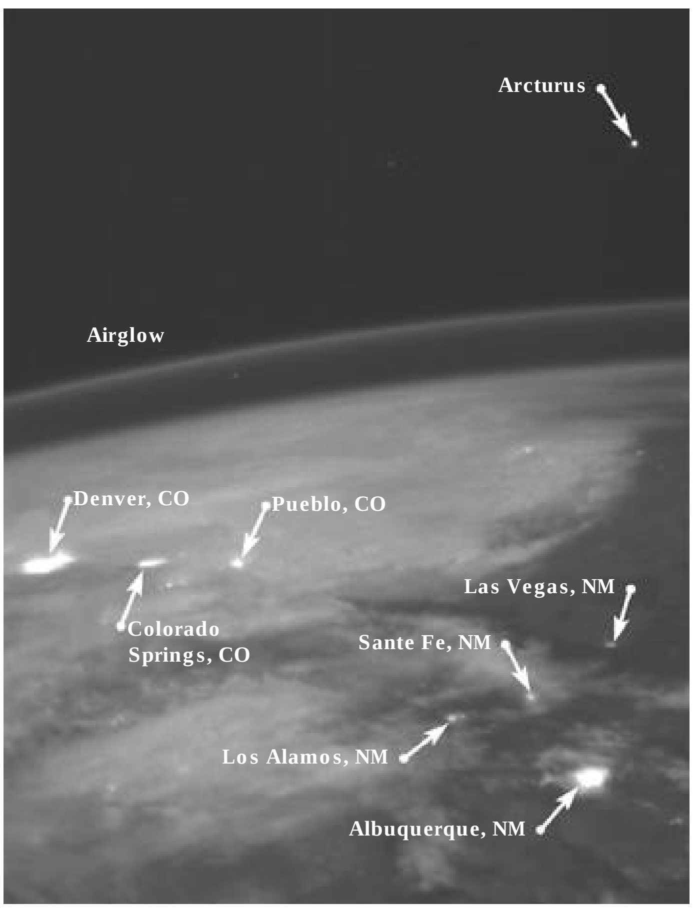


Figure 6. A Star Tracker view of Earth's limb (i.e., outer edge). The airglow caused by Earth's atmosphere and the light from major urban areas are visible.

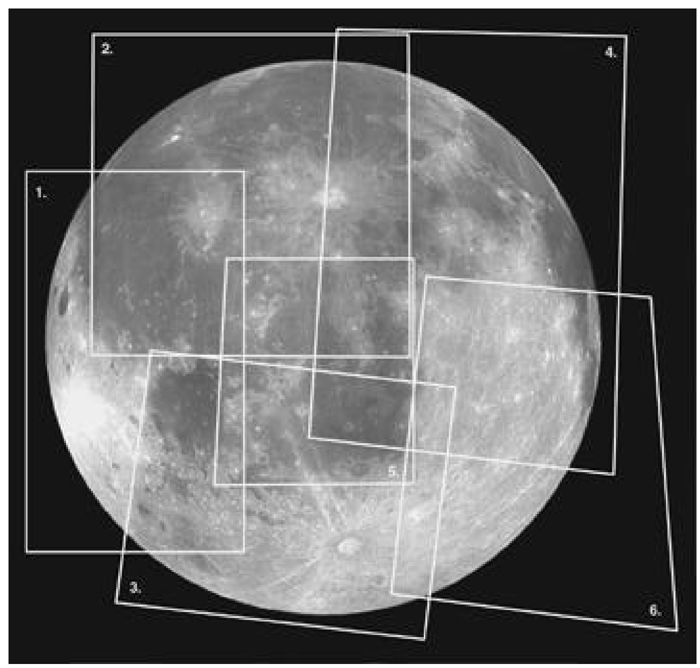


Figure 7. A composite of the Moon made from six separate Star Tracker images.

The LIDAR system took long strings of images with a resolution of about 10 m and range measurements with a precision of ±40 m at intervals of about 1 km. The LIDAR was also operated in burst mode to take up to eight range measurements per second. Near the lunar poles, the high-resolution LIDAR provided detailed pictures of the topography and geologic structure of the lunar surface. Early and late in the lunar mission, it was also used to take mosaics of high-resolution frames covering various Apollo and Surveyor landing sites. Craters up to 12 km deep were discovered during the Clementine mapping, far deeper than previously known.

Long-Wave Infrared Camera

To measure thermal emission from the Moon, LLNL, together with Amber Engineering, developed a small, 2.1-kg, long-wave infrared camera (Figure 14). This camera uses mercury–cadmium–telluride array technology to operate in the thermal infrared region of the spectrum (8 to 9.5 μm). Using a split-cycle cryocooler, the camera operates at 65 K (–208°C).

To appreciate the remarkable imaging capabilities of the cameras we contributed to the Clementine mission, Figure 15 compares a map of the lunar North Pole from the U.S. Geological Survey dating from 1985 with the state-of-the-art images made possible with our new components. An image from the long-wave infrared camera appears at the bottom right corner of this figure.

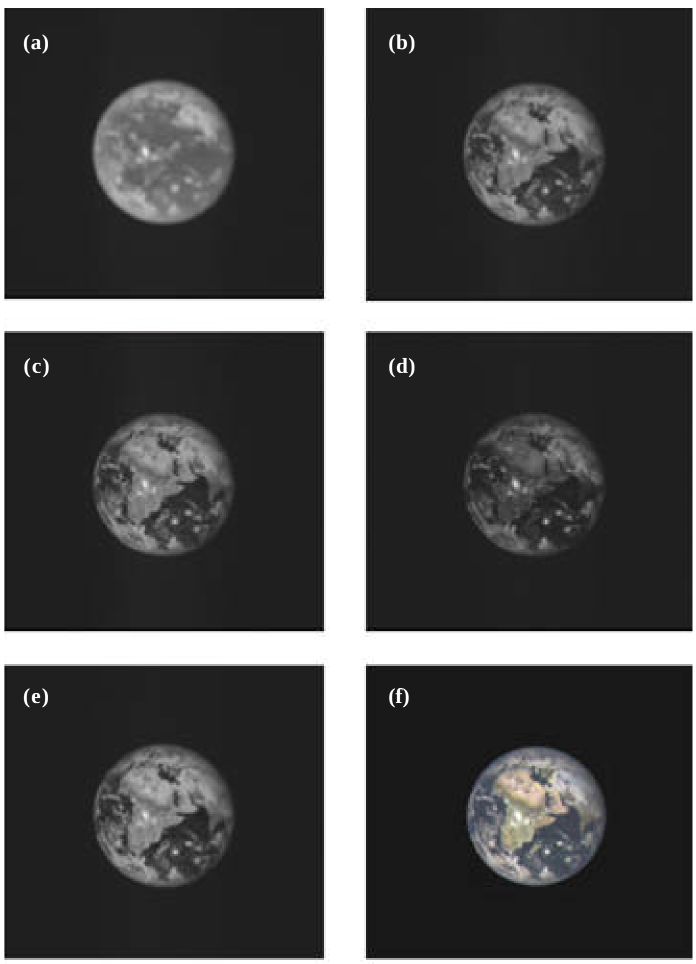


Figure 8. (a) to (e) The African continent on Earth imaged by the ultraviolet/visible camera at five different wavelengths on a clear day, March 13, 1994, from a distance of 384,000 km while Clementine orbited the Moon. (f) A broadband, composite view of the African continent.

Figure 9. The crater Tycho on the Moon, viewed by Clementine's ultraviolet/visible camera on February 28, 1994, from an altitude of 425 km. This image shows reflected sunlight at 1000 nm. The Tycho crater is about 80 km in diameter.

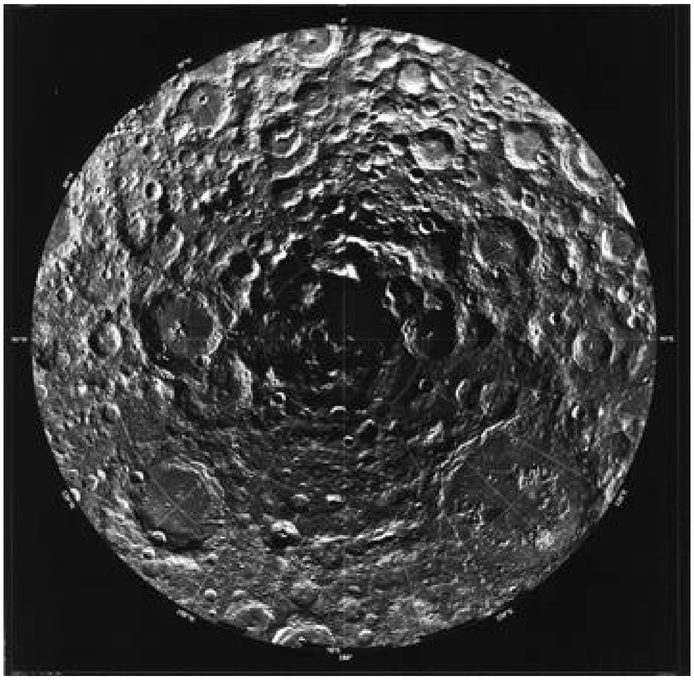


Figure 10. A mosaic of 1500 images taken by the ultraviolet/ visible camera of the lunar South Pole. The images reveal for the first time a 300-km-wide depression near the pole, probably an ancient impact basin, that may never receive sunlight. (Courtesy of NASA, Naval Research Laboratory.)

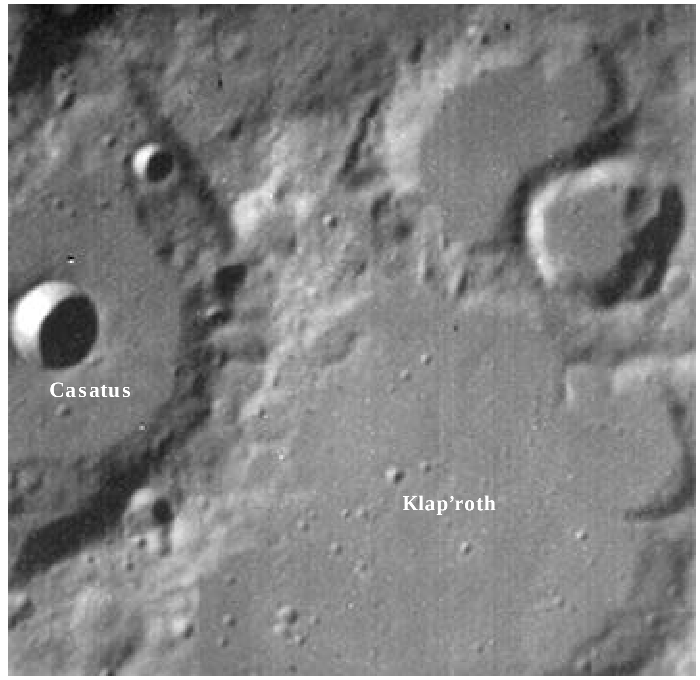


Figure 11. This partial view of the Moon's Casatus and Klap'roth craters was captured by the near-infrared camera on April 25, 1994. The image shows reflected light at 1.25 mm from an altitude of about 1300 km. The image is of an area 125 km ¥ 125 km.

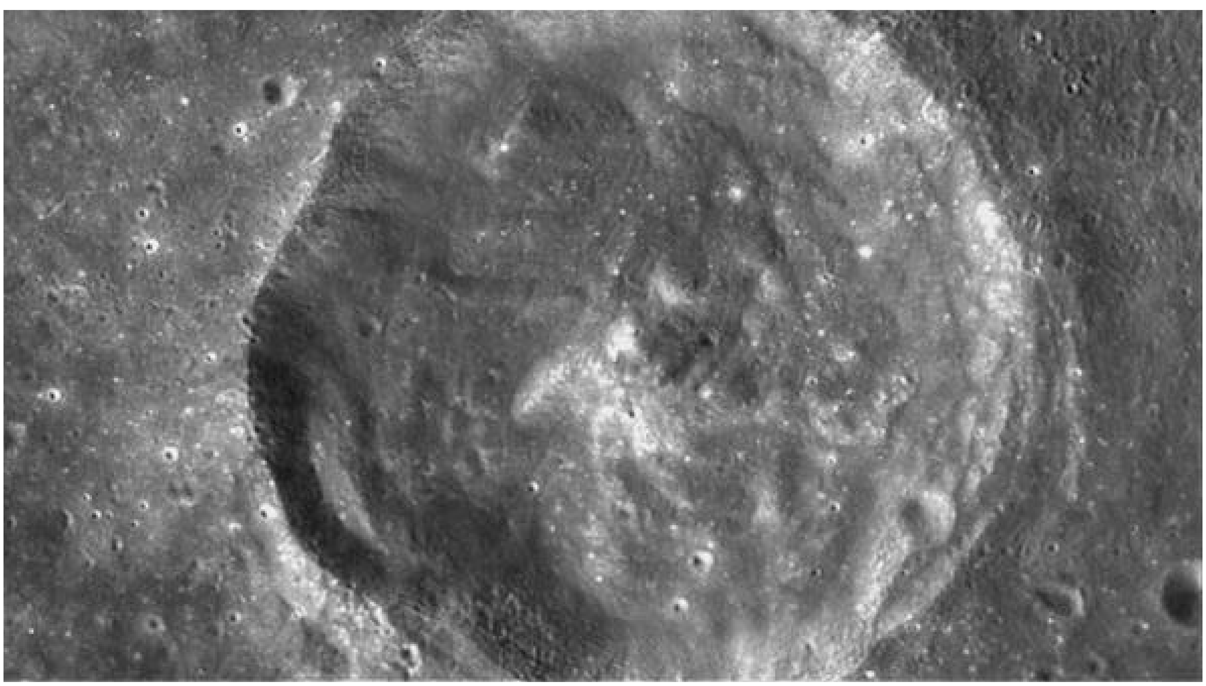


Figure 12. A view of the 35-km-diameter Rydberg crater taken by the near-infrared camera on March 6, 1994, from an altitude of 460 km.

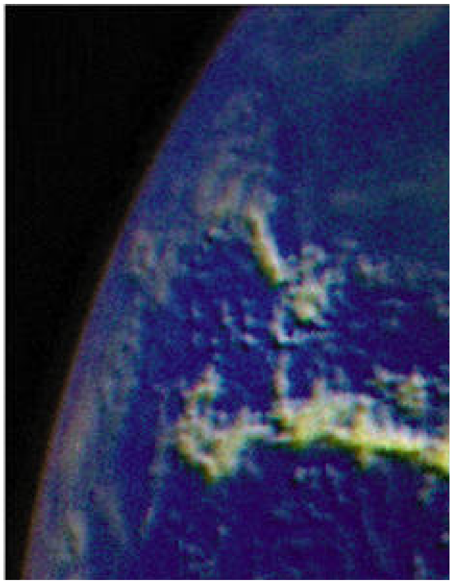


Figure 13. An image of Earth taken by the high-resolution camera on March 13, 1994, from lunar orbit at 1250 km above the surface of the Moon and 384,000 km from Earth.

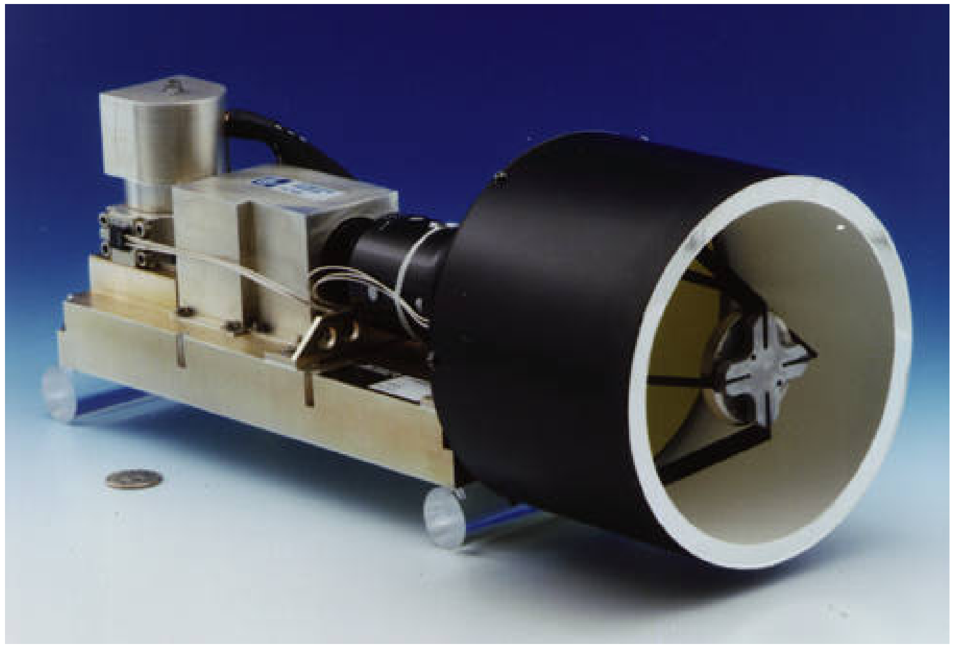
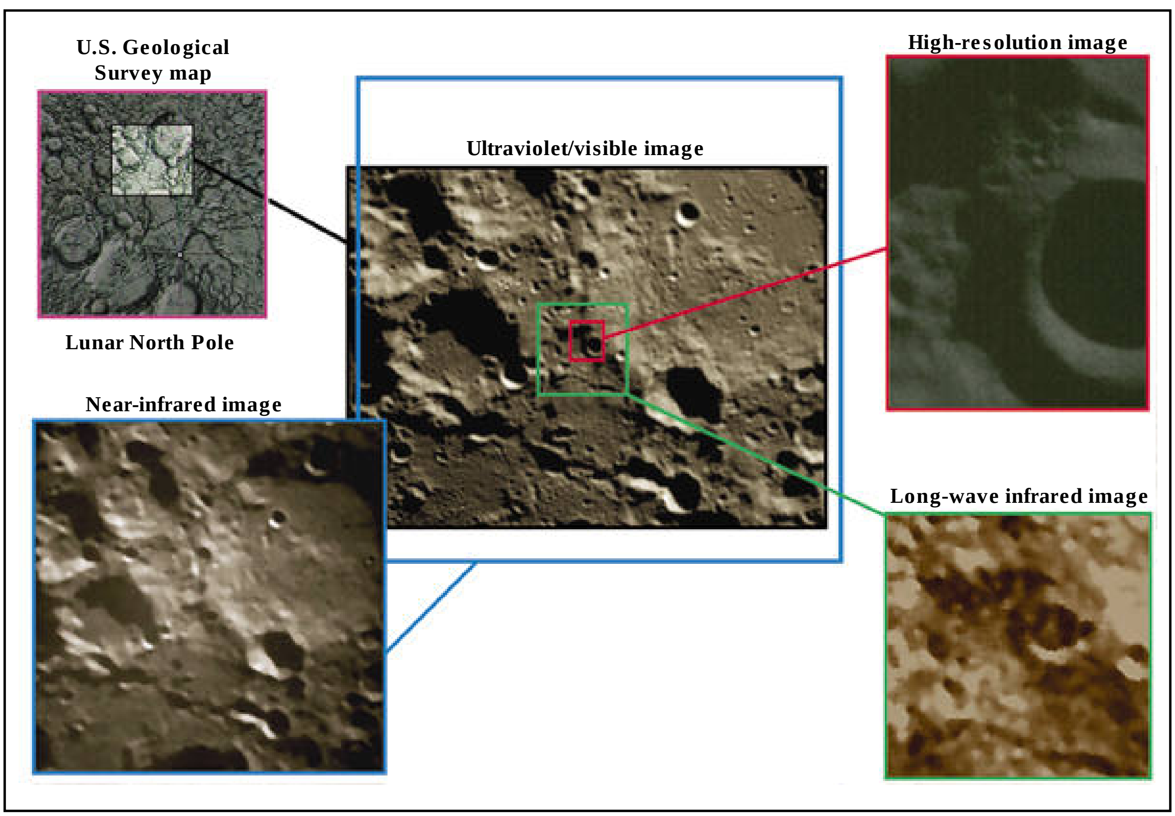


Figure 14. Operating in the thermal infrared region of the spectrum (8 to 9.5 µm), the long-wave infrared camera was used to measure thermal emission from the Moon's surface.

Figure 15. Detailed images of the Moon made possible by four of the LLNL-developed cameras that Clementine carried. A map of the lunar North Pole (latitude = 82° N; longitude = 104.6° E) provided by the U.S. Geological Survey can be used for comparison. This map (upper left), dating from 1985, was the state-of-the-art before the Clementine mission. Far greater detail is seen in images from the ultraviolet/visible, high-resolution, near-infrared, and long-wave infrared cameras. The latter four images were taken during Clementine's first lunar-mapping orbit on February 19, 1994.



Data Availability and Future Directions

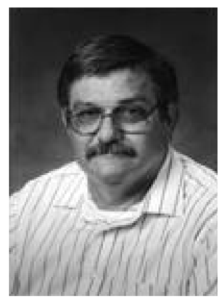
Clementine was launched successfully and on schedule. The amount of information it returned from lunar orbit alone will fill a small library of compact discs that will be distributed to NASA's Planetary Data System, a nationwide repository system for data returned from lunar and planetary flight projects and widely available to lunar and planetary scientists. Analyzing the data, including the results of a search for the existence of water on the lunar surface, will continue to occupy scientists for many years.

Students and teachers at all grade levels, and others across the country, can use Internet to access the pictures of the Moon and Earth taken by Clementine (see the box below). Information about the technology used to collect the data and explanations of how scientists are using these data are also available. This program is sponsored by LLNL's Science Education Program and the Department of Energy.

The miniaturized cameras, Star Trackers, powerful battery, and navigation instruments Clementine carried may aid in developing NASA's own line of small planetary missions (called Discovery) and its Martian environment survey (MESUR) program. Clementine may also provide a model for NASA's Lunar Scout—a pair of polar-orbiting spacecraft that will provide, among other things, a survey of the elements that make up the lunar crust and high-resolution images of the Moon's surface features.

Work funded by the Department of Defense's Ballistic Missile Defense Organization.

Key Words: asteroid—Geographos; imaging—Earth, Moon; missile—Titan IIG; satellite—Clementine; sensors—laser imaging, detection, and ranging (LIDAR) system, long-wave infrared (LWIR) camera, near-infrared (NIR) camera, Star Tracker Stellar Compass, ultraviolet/visible charge-coupled device (CCD) camera; spacecraft—Lunar Scout, Surveyor; space programs—Discovery, MESUR.



For further information contact Michael J. Shannon (510) 423-7580.

Exploring the Moon via Internet

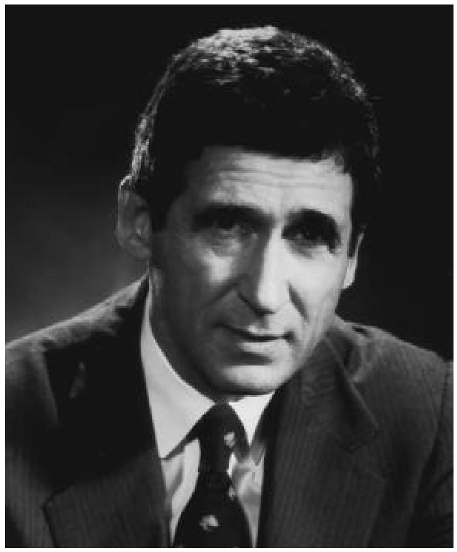
Several million images have been taken of the Moon, Earth, and various star fields using the six LLNL-developed cameras on board the Clementine spacecraft. An extensive database containing thousands of Clementine images and information regarding the Clementine mission is currently available on a network server on Internet. This server, clementine.s1.gov, resides at LLNL from which network customers around the world can download images and access other information.

To access the images over the network, you must have networking software (TCP) on your local computer and a file transfer program, such as ftp. Mosaic can also be used to access the images. Mosaic is a graphical tool allowing users to browse through the data in a point and click fashion, pointing and clicking on highlighted areas to display additional information relevant to the highlighted topic. To access the images via Mosaic, open the URL named http://clementine.s1.gov.

To access the server via ftp, the process and software are somewhat different for each type of computer. Here is a list of some of the most commonly used local processors and a brief description of how to access the server.

- Macintosh users must be running MacTCP and get the "Fetch" program from one of a number of sources (e.g., ftp.dartmouth.edu). Start Fetch to go to host, clementine.s1.gov, with user name ftp. Any password will do.
- PC DOS users must be running TCP and get ftp client software on their local computers. To get started, run this ftp program to go to clementine.s1.gov.
- PC Windows users must be running Windows with Sockets and get ftp client software for their local computer (e.g., get ws_ftp.zip in /pub/pc/win3/winsock on ftp.cica.indiana.edu). You will need to unzip ws_ftp.zip and run this ftp progam to go to clementine.s1.gov.
- Unix users must be running TCP and have ftp installed on their local computers (these are bundled with most Unix systems). To get started, type ftp clementine.s1.gov.
- VAX/VMS users must be running Multi-Net or UCX and have ftp on the VAX. To get started, type ftp clementine.s1.gov.

Uncertainty and the Federal Role in Science and Technology



On April 4, 1994, Ralph E. Gomory spoke to Laboratory employees about the new role of the federal government in supporting science and technology. This article is based on Gomory's talk, which was presented as part of the Director's Distinguished Lecturer Series.*

THE federal role in science and technology has been much discussed in recent years. Considerable dissatisfaction is apparent on both sides: on the part of the federal government and on the part of the scientific community. The scientific community complains of inadequate or misdirected support. Individuals in government ask why scientific leadership has not been translated into economic or industrial leadership. Some tend to characterize the scientific community as self-centered and self-serving.

Related discussions concern budgets, emphasizing certain applications, and setting scientific priorities. But priorities for what? What is it we are trying to do? What is the goal of all the effort and discussion?

Setting priorities can be most difficult if we do not have clear goals. If we don't know where we are going, it is impossible to have a sensible discussion about the fastest way to get there.

I believe that a lack of agreed-on goals has complicated the discussion of scientific support. Thus, I will attempt to suggest some possible goals for various aspects of scientific support by the federal government. But first, it helps to understand some elements of the federal science scene.

*The Director's Distinguished Lecturer Series was inaugurated in October 1977, the outgrowth of a suggestion by the Continuing Education Committee's subcommittee on physics. Each year, about half a dozen well-known scientists are invited to LLNL as distinguished guest lecturers. The lecture series serves to acquaint Laboratory people with the eminent scientists and their ideas. It also provides an opportunity for those scientists to learn more about the Laboratory and its research.

Support of the Individual Investigator

By any reasonable standard, support of basic science—especially support of the individual investigator—has been the most successful of the federal government's roles in science and technology. A policy of support for basic science emerged in the post-World War II period. The great achievement of scientists during the war—for example, the atomic bomb and radar—gave politicians and the public a feeling for the immense power that resides in scientific knowledge. The thought that led to the policy of support, namely "Science is power," was rewarded by scientific successes that have transformed and continue to transform the world.

One example is the transistor, an invention that grew out of the basic understanding of solid-state physics in the same way that the atomic bomb grew out of understanding the atomic nucleus. Another is molecular biology, with its remarkable revelations about the basic functions of all living things and the enormous and emerging consequences of this technology.

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When we seek to justify federal money spent on the individual investigator, we have, in reality, set an easy task for ourselves. We don't have to look ahead and speculate about individual research; we only need to look back at a great history of success. The idea of supporting the individual investigator works. The approach works, whether it is measured in terms of scientific progress or of advancing the material level of the world.

Despite that success, however, there are problems today within the basic science community itself. Researchers face high rejection rates from the supporting agencies, such as the National Institutes of Health (NIH) and the National Science Foundation (NSF). We have seen a diminution of interest in science and engineering on the part of students. There is a long pipeline to the Ph.D. degree and difficulty in getting jobs at the other end of that long pipeline. Despite a remarkable record of success, we may not be producing a reasonable way of life for the scientist.

In trying to understand what is going on and what to do about it, we immediately encounter confusion and a great divergence of views. Some say the answer to the high rejection rate for grants is simple. Scientists clearly do good work; we should simply give them more money. We should fund any good idea because it's worth it. Others say that money spent on science has been increasing steadily, even accounting for inflation. To increase it more under the present ground rules will produce an ever-increasing population of research scientists who will be claimants for the same limited number of desirable jobs. More research scientists would mean still more competition for grants.

The remarkable fact is that we don't know what is going on. We don't have the most basic model of the process of generating researchers. As a result, what does happen is much more a political process than a thought-out process.

What we would actually do if we had a decent picture is also unclear. What would our goals be? Is it really possible to articulate goals for basic science even if we had a clear picture of what is going on?

Most of us automatically reject goals that set specific aims for scientific subjects. However, as a country, we could set goals in a different way. We could have a goal of being world-class in most major

Ralph E. Gomory

Ralph E. Gomory has been president of the Alfred P. Sloan Foundation since 1989. Before that, he was a senior vice president of IBM, where he was director of research for almost 20 years. He has written extensively on the nature of technology and product development, research in industry, industrial competitiveness, and economic models involving economics of scale.

Gomory has won many honors and prizes, including the Lanchester prize, the John Von Neuman Theory prize, and the National Medal of Science awarded by the President in 1988. He was named to the President's Council of Advisors on Science and Technology in 1990 and served until March 1993. He holds a bachelor's degree from Williams College and a Ph.D. in mathematics from Princeton University.

scientific fields. Today, we don't have such a process goal, and we don't even have a debate. I will return to this thought later.

What we should remember is that basic science and its support by the federal government has worked. It has benefited the world in obvious ways and should continue. However, we should also stop flying blindly toward an unknown destination for the good of researchers and the rest of the world as well.

Support for Megaprojects

I distinguish between two types of megaprojects: those that I call real science, and those that are often referred to as science and justified as such but are not science.

Real scientific megaprojects include various orbiting telescopes, scientific satellites and space probes, and, until recently, the most prominent member of the group, the Superconducting Super Collider. These types of megaprojects often represent good science. But, do such endeavors represent the right way to prioritize and spend our science dollars? For example, we spend about $2 billion a year on unmanned space probes. This is about the same amount of money that the NSF spends each year on individual investigators. Historically, the individual investigator has been far more productive.

Perhaps we could deal better with scientific megaprojects by incorporating their cost into the relevant scientific fields, such as astronomy, earth sciences, or physics. In this way, we could decide how we want to spend money to obtain world-class standing in a particular field. With such a goal, at least a sensible debate could ensue.

The second type of large project is what I call the nonscience megaproject. Space is the best example of this group. The space program originated in our race with the Soviets. Few who were around at the time will forget the extreme national reaction that greeted Sputnik. Edward Teller, in his usual picturesque way, asserted that we had suffered a defeat worse than Pearl Harbor. Out of this disturbed national atmosphere came a political decision to put men on the Moon. We did so to surpass the Soviets, not to settle the question of what the surface of the Moon is like.

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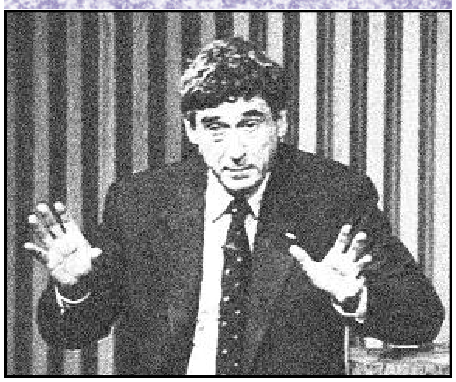

Given this capsule view of the origins of the space program, we might wonder whether such a large program is necessary today. Our rivalry with the former Soviet Union has diminished. Its successor state, Russia, has abandoned communism and no longer represents a world-class ideological threat. Yet, we are still spending more money on the space program ($14 billion per year) than the combined budgets of three NSFs and one NIH.

If we ask whether the space program in its present form is necessary today, we would get more than one answer. We would be told, for example, that the program:

- Is important science.
- Recruits people into science.
- Contributes to civilian technology.

These explanations are all science- and technology-oriented, and they are all somewhat true. We might also be told—and here I think we are closer to the truth—that the manned exploration of space, and perhaps the eventual settling of space by people, is a national goal in itself, quite independent of science. But if exploring and settling space in this way is a national goal, then let us articulate that goal and debate it rather than obscuring it with scientific justification. If we accept this national goal, let us also decide to pursue it at a proper pace, which would not necessarily be the pace appropriate to a race with the former Soviets.

In contrast to basic science, space exploration, whatever its rationale, doesn't perform some obvious or useful function now in the absence of an intense American–Russian rivalry. For this reason, we need to clarify what we are doing. There is no scientific purpose that could justify the enormous bill. If the goal is actually something else, like manned exploration of space, let us articulate that as a national goal and then determine the pace and rate of expenditure that are appropriate for that goal.

Science in Support of National Goals

We have many national goals, although they are usually only dimly articulated. We have a goal of making economic progress and of being economically competitive. We have the goal of improving the health of Americans and of protecting the environment. The goal that I know the most about is economic competitiveness.

In the U.S. in recent years, we have graduated from the idea that science alone guarantees industrial leadership to the idea that science and technology plus the rapid commercialization of new ideas are what matter. At the same time, the federal government has moved from a position of supporting only basic science to a position of supporting generic or precompetitive technologies.

Behind this shift is the thought that turning new technologies into real products is the issue. The notion is that we in the U.S. have the ideas, but others commercialize them. However, if the commercialization of new technology were really the problem, it would be very convenient because we could then use science and technology policy as a substitute for an industrial policy. Industrial policy, in a broad sense, is and has been a complicated and questionable subject in the U.S.

Unfortunately, this view of the problem flies in the face of the facts. The U.S. has not had an innovation problem to date, even in the sense of commercialization. The industries that make up the balance-of-payments deficit are textiles, automobiles, semiconductors, and consumer electronics. I know nothing about textiles, but the problems in the other three areas have had little to do with innovation. The problems have everything to do with manufacturing.

For these industries, it simply isn't true that we had the good ideas, and others commercialized them. In fact, they are all industries where U.S. companies commercialized the original ideas and grew to have a strong position in the mature field. However, they subsequently lost that position to competitive products with superior quality and lower manufacturing costs and to competition having a rapid development cycle leading to rapid, incremental improvement in the product.

"We need to work backward from the competitiveness goal and the needs of industry rather than forward from the latest scientific event."

To date, quality, speed, and manufacturing have been the real strength of the competition rather than the much-publicized advanced-technology efforts. Until we face that reality, we are unlikely to make progress.

In this area as in others, we need to set a goal—contributing to American industrial competitiveness through science and technology. We then need, in close cooperation with industry, to discover exactly what science and technology programs will actually contribute in the way of giving us competitive industry. We need to work backward from the competitiveness goal and the needs of industry rather than forward from the latest scientific event. Of course, there will be different views, but I believe a sensible outcome would emerge. The result is likely to be a mix of the old and new, of high technology and manufacturing technology.

In working toward this goal—contributing to industrial competitiveness—we must also consider the fact that there are several very different situations in the realm of technology that call for different approaches. Prominent in the minds of academics and many in government is what I call the "linear model of technological progress." In this model, an idea is born in science, it progresses through a technology stage into new products, and it gives rise to a new industry. The transistor went down that path a while ago. Molecular biology is evolving that way today. Here, we can imagine a government role in fostering the underlying science and possibly, but not certainly, helping new enterprises that may be struggling. The latter role is most plausible in areas that have a small market component. For example, the government might play a role in supporting work toward the cure of rare diseases where the projected income could not support the development effort.

A more difficult task is helping an already-established industry, such as semiconductors, where the issue is not new technology but the rapid, cyclic improvement of what is already there.[1] In this case, it is essential that industry participate from the beginning. Whatever is to be contributed must fit into an already-existing industry, its tools, knowledge, and plants.

Most difficult of all is the case where we would like to enter a technological industry that exists only outside the U.S. Here, fostering technology is not enough. Even if we understand liquid crystal displays, for instance, being able to manufacture and market them competitively is a quite different matter. Technology is only part of a much larger game, and here we are on the fringes of true industrial policy.

Today, in working toward a competitiveness goal, we are largely in the realm of experiment. We have some new programs, like those of the Department of Commerce and Sematech (a consortium of U.S.

semiconductor firms established to compete more effectively in the global marketplace). Then there is the large and daunting problem of turning some of our national laboratories to a new direction in support of competitiveness or some other national goal. Once we have clarified our goal in this area, and once we decide that we need to work backward from that goal and see what is needed, experimenting will certainly be the right thing to do.

Setting Goals for Science

In looking at the present federal effort, we have seen how the support of basic research became possible after World War II, how the space program emerged from our rivalry with the Soviet Union, and how the exigencies of competitiveness are having some effect on the federal science and technology scene. The situation today has emerged from a normal historical process. However, we should ask ourselves whether the historical motivations are still correct, and even if they are, how correct. Even if most of us agree that government support of basic research is an idea that made sense in the past and makes even more sense today, that alone does not answer the question of how much basic research is enough.

What I have to say on this question is based on some ideas I have been pursuing for some time. It is also based on the recent (1993) report issued by the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine entitled "Science, Technology, and the Federal Government: National Goals for a New Era.[2]

Basic research is funded because of the belief that something broadly and directly useful will eventually come of the scientific effort. Scientists do not often think about usefulness, but scientific funding ultimately rests on society's hope for and expectation of practical results. This expectation has been historically fulfilled in that basic science has already provided major practical returns, such as the transistor and other examples given earlier.

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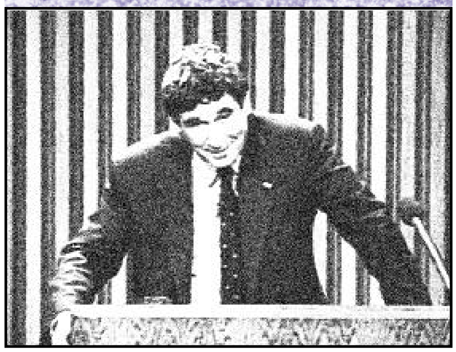

However, the overall success of basic research has not prevented people from wanting to fund only those areas within science that can be seen to be useful. At the same time, such individuals question the support of areas that do not seem to be useful. In contrast, scientists have generally wanted funds to do what they think matters. They often decry research funding directed at useful goals as misguided and shortsighted.

I think that both of these views represent partial truths, and neither is the whole story. To see why, I would like to introduce the following "uncertainty principle" for scientific funding: We can see when some area of science is useful or is about to be useful, but we can't see that some area of science will be useless.

Consider the first half of this sentence. Some fields of science demonstrate their practical potential in a clear way at a certain point. Molecular biology today, and for some time in the past, is an example. In fields like this, the U.S. may well decide that it wishes to lead the world and be the first to benefit from the useful consequences. The practical consequences—the usefulness to society—can take many forms. They might be contributions to economic competitiveness, to national health goals, or to national environmental goals. Historically, the practical consequences have often been contributions to national defense goals.

Note that the benefits from world leadership are outside science itself. They have to do with the goals of society, not with whether one field of science or research is more exciting than another.

Now consider the second half of the sentence: We can't see that some area of science will be useless. This statement is more than something scientists merely want to believe because it justifies their pursuit of whatever they want to pursue. It is also a reality. The history of quantum mechanics is a good example.

In the 1920s, there was no subject more pure and more esoteric than quantum mechanics. At first, we had the uncertainty principle and the baffling puzzle of electrons that behaved like waves one moment and particles the next. Quantum mechanics was a subject with exciting scientific and even philosophical impact, but nothing could have been farther from real applications. By the 1930s, quantum mechanics began to have an effect on the field of solid-state physics. After the war, we gained an improved understanding of the fundamentals of crystalline solids, which led to a better grasp of the role of trace impurities and their effect on the flow of electrons. The transistor was not far behind. The transistor had a tremendous impact on computers and on electronic devices of every sort. These devices now affect the everyday life of us all. Not much more than 30 years separated the esoteric and apparently useless from the enormous impacts we now experience each day.

This example shows that practical discoveries do, indeed, turn up in the course of pursuing the most basic knowledge. What is more, we can expect the process to keep happening. Sometimes, people outside science think that the process is pure serendipity, that if we turn over enough rocks, every now and then we will find a diamond. However, the actual process is nothing like that. In reality, it is the systematic exploration of a significant piece of the natural universe. It is not surprising that when we begin to understand, in a fundamental way, important pieces of the universe—for example, how solids hang together or how living beings function at the molecular level—at some point, the understanding will allow us do things we couldn't do before.

The two halves of the uncertainty principle lead to these two consequences[3]:

1. The U.S. should maintain clear world leadership in some selected areas of science.
2. The U.S. should be among the world leaders in all major areas of science.

The first conclusion is the clear recognition of the demonstrated usefulness of a scientific field. The selection of fields for world leadership is a social, not a scientific, judgment. It is a judgment that money spent on a selected area will give a large social return.

The second conclusion is the explicit recognition of two things: the unpredictability of basic research, and the fact that scientific knowledge is not a free good. We cannot benefit from scientific research, even in a world in which scientific communication is both free and international, unless we have paid the price of being a significant participant.

"We can see when some area of science is useful or is about to be useful, but we can't see that some area of science will be useless."

If the U.S. is among the world leaders, when something happens anywhere in the world and a field begins to show practical promise, we would be in a position to participate. For example, the possibility of high-temperature superconducting materials suddenly appeared a few years ago in the work done in Zurich, Switzerland. These materials had the promise of cheaper electricity and many other applications. Americans were major participants in the field almost at once. The U.S. should always be at least in that position.

Now let us apply this way of thinking to two current examples. First, consider the Superconducting Super Collider (SSC). Is particle physics a field where, because of its clear contribution to society, we must be out ahead of the rest of the world? If we want to be clear leaders, we should build our own SSC. If we are content to be only among the leaders, we should try to work out with the Europeans a cooperative arrangement to advance the field. The question is this: Do we need clear leadership in particle physics for societal reasons? The answer is not a judgment to be made by scientists, although it needs scientific input. The simplest test is to ask if there is a large and demonstrated payoff from the field in terms of its contribution to the economy, medicine, or any other such societal goal.

I think that the record of particle physics, to the extent that I know it, simply does not support the notion of a large societal payoff from building the SSC. Nor is there any reason, at the moment, to suppose that the future will be sharply different from the past. I would personally conclude that this is not a field for clear U.S. leadership, that the SSC should never have been started, and that we ought to go back to the drawing board and see if we can work out something with the Europeans that will allow us both to move forward in particle physics.

Turning again to the topic of molecular biology, I think we would come to the opposite conclusion. This field has a clear relation to an emerging industry as well as applications to health. This country might well decide that, in the interests of national health and of the emerging biotechnology industry, we want to be well ahead of the rest of the world.

Other Consequences and Conclusions

The goal of being among the leaders in a given field is a measurable goal. It involves a comparison of the level of science in the U.S. in a particular field with the level of science for that field in other countries. We are among the world leaders if we are roughly on a par with the work done abroad. Of course, many other questions need to be answered as well. For example, do we compare ourselves with other individual countries or with Europe as an entity? Such questions need to be worked out in accord with the basic issue of whether we are in a position to react and participate if the field suddenly changes.[2]

Note that the stress here is on a comparison not merely with other countries, but a comparison within a particular field. Testing whether we are among the leaders in a given field of physics—such as condensed-matter physics—does not call for a comparison of funding for condensed-matter research with funding levels for a different field of physics or some field within chemistry. It also does not call for arguments about whether one field is more exciting than another. It says we should measure ourselves against the world standard in each of these fields.

In addition, we do not need to make a comparison of big science with little science. The goal of being a leader—or a clear leader—should establish the mix of big science and individual investigator science in that field. The mix that is right for leadership in particle physics surely is not right for leadership in condensed-matter physics. What matters is to get it right for each field, not to add up the big science and the little science across the board and make a meaningless comparison of the totals.

I think the time is right for a new era in federal support of science and technology. I think it is possible to clarify where we are going to set the goals and how we are going to work toward them, while at the same time respecting the many unknown outcomes from basic research. If we do this, society will benefit even more than it has in the past, and science itself will be supported in a more stable way.

Key Words: science and technology—basic research, federal support, goals, individual investigators, large projects.

Notes and References

1. R. E. Gomory and R. W. Schmitt, "Science and Product," *Science* **240** (4856), 1131–1132, 1203–1204 (1988).
2. Committee on Science, Engineering, and Public Policy, *Science, Technology, and the Federal Government: National Goals for a New Era* (National Academy Press, Washington, D.C., 1993); available from the National Academy of Sciences, 2101 Constitution Ave., N.W., Washington, D.C., 20418.
3. These are the two main conclusions of Reference 2. These concepts are also closely related to the following: R. E. Gomory, "Goals and Priorities for the U.S. Government's Role in Science and Technology," Testimony before the House of Representatives Subcommittee on Science (Committee on Science, Space, and Technology, April 28, 1992); R. E. Gomory and H. Cohen, "Science: How Much is Enough?" *Sci. Am.* **269** (1), 120 (July 1993); R. E. Gomory, "Goals for the Federal Role in Science and Technology," *Phys. Today* **46** (5), 42–45 (1993).

For further information contact Ralph E. Gomory, Alfred P. Sloan Foundation (212) 649-1649.

Abstracts

The Clementine Satellite

When the Clementine satellite was launched from Vandenberg Air Force Base on January 25, 1994, it represented the first U.S. satellite to the Moon in more than two decades. Sponsored by the Ballistic Missile Defense Organization, the Clementine experiment was primarily designed to demonstrate lightweight imaging sensors and component technologies for the next generation of Department of Defense spacecraft, using the Moon, the near-Earth asteroid Geographos, and its own solid-rocket motor as imaging targets. Its secondary mission was to provide scientific data on the mineral content of the lunar surface and on the formation of planets in our solar system. Plans called for Clementine to encounter Geographos on August 31. On May 7, however, a processor malfunction drained the attitude-control system of all its fuel, effectively canceling the Geographos portion of the mission. Nevertheless, the planned technology-demonstration and lunar-mapping parts of the mission were a success, with the LLNL-developed on-board cameras returning more than 1.5 million images of the Moon at spatial resolutions never before attained.

Contact: Michael J. Shannon (510) 423-7580.

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Ralph E. Gomory was a recent participant in LLNL’s Director’s Distinguished Lecturer Series. Gomory is an eminent figure in both research and industry. He has been president of the Alfred P. Sloan Foundation since 1989. Before that, he was a senior vice president of IBM, where he was director of research for almost 20 years. He has written extensively on the nature of technology and product development, research in industry, industrial competitiveness, and economic models involving economics of scale. In his April 4, 1994, lecture, Gomory addressed some of the tensions, conflicts, and possible goals related to federal support for science and technology. In particular, he asserted that a goal must first be clearly set—namely, contributing to American industrial competitiveness through science and technology; then, working in close cooperation with industry, decision-makers can discover what science and technology programs can contribute to U.S. industrial competitiveness.

Contact: Ralph E. Gomory, Alfred P. Sloan Foundation (212) 649-1649.